International Journal of Mechanical and Production
Engineering Research and Development (IJMPERD)
ISSN (P): 2249–6890; ISSN (E): 2249–8001
Vol. 11, Issue 4, Aug 2021, 173–192

A REVIEW OF SOLAR POWER, DESALINATION TECHNOLOGIES, PRE-FILTRATION, POST-TREATMENT AND ENERGY RECOVERY IN DESALINATION – SUSTAINABLE DESALINATION PLANTS

FREDDIE INAMBAO, VIASHNA SOMA, CONNOR GONS, THEMBINKOSI NDAWONDE, NHLANHLA LANGA

Department of Mechanical Engineering, University of KwaZulu-Natal, Durban, South Africa

ABSTRACT

Due to population growth, there is an increasing demand for alternate supplies of potable water. Desalination technologies provide an effective solution to meet water demands by purifying saline water. Desalination systems have become popular in developed countries and show promise in rural areas when combined with renewable energy sources. This paper presents a review of solar power, desalination technologies, pre-filtration, post-treatment and energy recovery in desalination, and sustainable desalination plants. A critical analysis is conducted of the design of a photovoltaic (PV) stand-alone desalination system, particularly focusing on its solar power components, reverse osmosis desalination technology, pre-filtration, post-treatment and potential energy recovery devices.

KEYWORDS: Desalination, Solar Power, Reverse Osmosis, Energy Recovery

Received: May 05, 2021; **Accepted**: May 25, 2021; **Published**: Jun 28, 2021; **Paper Id.**: IJMPERDAUG202115

Original Article

1. INTRODUCTION

Water scarcity is a problem that extends globally, affecting first and third world countries alike. The United Nations General Assembly placed “clean water and sanitation” among the 17 Sustainable Development Goals (SDG’s) hoped to be achieved by 2030 (Department of Economic and Social Affairs, 2016). Barriers to achieving this goal include climate change, poor water management and an increasing demand on fresh water supplies from a growing population. Addressing climate change and sustainable water management through stringent policy enforcement is challenged by governance structure, social barriers and a lack of capital and capacity to execute management policies (Greve et al., 2019).

Conservative water usage and legislation protecting fresh water supplies are effective means of ensuring water security. However, the difficulty in implementing relevant legislation has promoted the idea of technological innovation as the key to water security.

A paper published in the Natural Resource Forum (Department of Energy, 2008) investigated scientific and technological innovations taking place in the prior 50 years that offer a solution to the problem of water scarcity. In the paper four technologies are presented on the grounds that they “provide relatively easy, quick and affordable” means of addressing the problem. The technology of interest to this design team is the desalination of saline water to produce potable water.

The desalination process can be applied effectively in coastal areas or inland areas where the only available water supply is underground brackish water (Department of Energy, 2008). Increased interest in desalination can be attributed to technological advances and the rising cost of conventional water production. Developments in

membrane technologies in the fields of chemical engineering have resulted in tougher membranes with longer life cycles (Bathia, 2014). According to a study of seawater desalination costs and technology trends conducted by Lenntech (2016), the cost of mainstream water production from rivers, dams and aquifers has risen by 50 % to 100 % in the past two decades. At the same time, a decrease in the cost of desalination between 50 % and 100 % has been noted.

A sector where small-scale reverse osmosis devices have been applied effectively is the maritime industry. The installation constraints of having to be compatible with small sea vessels where space and power supply are limited, has given rise to compact systems operating on small scale off-grid power systems. Systems have been designed to achieve volumetric production of 460 L/h while consuming as little as 3.5 kWh/m^3 (Valavala et al., 2011). To achieve this, systems need to implement efficient membrane technologies and energy recovery devices, and some systems have benefitted from smart controllers that regulate system parameters to ensure efficiency of the system under different operating conditions (Valavala et al., 2011).

In rural communities where the availability of clean drinking water is an issue, it is very common to find that the availability of electrical energy is also an issue. These isolated and secluded areas that are neither connected to municipal water nor electrical supply grids require local power generation. Renewable energy sources offer the best alternative to centralized power plants, reducing capital infrastructure costs (Adams, 2013). A feasibility study of the installation of a PV standalone system in rural India (Pyzalska, 2007) concluded that in remote areas, investment by the government in sustainable, stand-alone power supply would be more feasible than establishing and maintaining electrical lines to those areas.

Solar, wind, small-scale hydro and biomass are playing an increasingly larger role in the world's energy production. Where renewable energy sources were always an attractive, environmentally friendly alternative, they are now beginning to challenge the feasibility of modern fossil fuel based, centralised power supply.

The capacity for solar power in South Africa is evident from the existing solar projects alone – South Africa houses 8 of the 10 largest solar projects in Africa (Fares et al., 2019). In South Africa, the average annual global solar radiation is 220 W/m2 compared to 150 W/m2 in the USA and 100 W/m2 in the UK (Mechell & Lesikar, 2010). Considering the solar capacity present in South Africa and the proposed project, the design of a stand-alone PV powered desalination plant will be explored further.

2. PV STAND-ALONE SYSTEMS

The stand-alone PV system is characterised by its operation independent of a municipal distribution grid. The system most often incorporates battery storage for maintaining continuous power supply to a load system (Valavala, 2011).

2.1 Components of a Stand-Alone PV System

2.1.1 PV panel

The photovoltaic (PV) panel is responsible for converting photon energy from the sun into electrical energy. The panels are made from semiconducting material – most often silicon (Adams, 2013). The smallest unit of the PV panel is the solar cell which can be connected in series or parallel configurations to form solar modules. These modules are arranged in electrical networks to form the PV panel (Adams, 2013).

Three major types of solar panels exist: polycrystalline, monocrystalline and amorphous/thin film panels (Adams, 2013). The panels differ from one another in their composition and manufacturing processes and perform differently under various environmental conditions. The performance of these panels is discussed in section 2.3.

2.1.2 Controller

The controller is responsible for charging and discharging the battery pack. When the load requirements of the system surpass the power supply from the panels, the controller discharges the battery to the load appliances. When the panels produce surplus power, the controller manages the charging of the battery pack. The battery cells are often the limiting factor in the life of a PV system. Investing in a good charge controller is advised for system performance and longevity.

2.1.3 Battery storage

Battery storage is optional in PV systems. The advantage of implementing battery storage is having system autonomy when the panel array is not producing power. The batteries used in PV systems undergo charge and discharge cycles regularly as power supply and demands vary. The most commonly used batteries in PV systems are lead-acid batteries because of their availability in various sizes and their low cost. Lithium-ion batteries are a larger upfront investment but are maintenance free and have a much longer lifespan than lead-acid batteries (Pyzalska, 2007).

2.1.4 Inverter

The inverter is responsible for allowing compatibility between the AC loads in the system and the DC power supply from the solar panel array and the battery storage. The efficiency of the inverter is defined by its ability to convert DC power with minimal power loss. Modern inverters operate at generally high efficiency (90 % to 95 %) but are affected by load variations in the system (Fares et al., 2019).

2.1.5 Load

The system load is the sum of all components being powered by the PV array. Loads can be classified as either DC or AC loads and the distinction is important in the design and specifications of components in the system. Special note needs to be made regarding compressors and motors where power surges are expected.

2.2 Modelling and Design of PV Stand-Alone Systems

2.2.1 Models of PV systems

Several mathematical models for the modelling and simulation of a stand-alone PV system are presented in a 2008 paper by the University of Craiova (Mechell & Lesikar, 2010). The components of the PV system are modelled by equivalent electrical circuits governed by basic electrical principles. The advantage of this modelling technique is the ability to treat each component as an electrical block with input and output parameters, making it easy to implement this model in MATLAB software. Efficiency values of the inverter and controller can easily be factored into the models. An important factor to note is the conclusion of a 15 % difference in simulated and tested panel efficiency.

An alternative method of modelling and simulation of PV systems is through software programs. The design approach of a stand-alone rooftop Solar PV system for rural India (Khalipour, 2019) makes use of five software tools for the aid of simulating and sizing the PV system, economic analysis of the system and productivity evaluation. To achieve accurate simulation results it is vital to collect accurate geological data on the irradiance levels and climatic conditions in the proposed area. The team also used standard industry practice calculations based on component specifications and known irradiance values in the area to size the various components of the system. From these results it was established that the various software packages performed accurately in sizing the proposed system.

2.2.2 Standard practices in design of PV stand-alone systems

When designing and selecting the components of a stand-alone PV system, standard practices can be applied effectively in component selection. The method is simple to carry out and provides a quick means of estimating the size of components needed for the system based on the load requirements. This is helpful when making quick cost estimations for proposed system installations.

This method was applied in the design of a rooftop PV system (Khalipour, 2019) and results matched the simulated results generated from software design programs. Worth noting from the results of this method were that higher accuracy was obtained when the loads from the system were separated into DC and AC loads, respectively. This ensured that inverter efficiency values were only applied to AC loads.

It is also worth noting that when selecting an inverter for the system it is common practice to select an inverter that is 25 % to 30 % larger than the wattage requirements of the system and that large motors/compressors require that the inverter be chosen at three times the load wattage to account for surge charges.

Points worth noting in battery selection is that the depth of charge factor specified by the manufacturer be applied when determining the required battery size. This factor accounts for the battery not being able to discharge 100 % of its potential stored energy. Finally, the controller must be sized against 1.3 times the PV panel rated short circuit current. This will protect the system components from high currents.

2.3 Performance of PV Stand-Alone Systems

2.3.1 Performance indicators

The performance ratio (the ratio of actual and theoretical power generation) is a simple indicator that can be used to gauge the performance of the PV system as a whole (United Nations, 2013). Since the theoretical power output is determined with the efficiency of the PV panels, inverter, battery and controller mind, the performance ratio can be an indication of how greatly other climatic or internal system factors are affecting the system's performance.

The capacity factor of a system can be calculated as the ratio of total power output over a given period to the power output achievable by the system if it ran at 100 % output capacity. The capacity factor is best calculated over the period of a year – this gives a good indication of seasonal climate conditions on system performance.

In an investigation of the performance of seven rooftop solar systems, the performance of two system inverters were investigated (United Nations, 2013). The study investigated the inverter efficiency in each system over a one-year period and found that the largest inverter efficiency range over a year period was 0.2 %. This should not be taken to mean that inverter efficiency is of little concern in system design. Research conducted into the effect of inverter efficiency on the performance of stand-alone PV systems (Fares et al., 2019) concluded that in systems where load requirements vary over a large range during the day, inverter efficiency is of importance when sizing the PV panel array. For systems installed as an alternative to grid power, performance may also be evaluated against the cost versus return of the instalment and the environmental impact of the installation.

2.3.2 Factors Affecting System Efficiency

The performance of solar cells is greatly dependent on solar radiation levels and temperature. A 2015 study conducted in Abu Dhabi (United Nations, 2103) evaluated the performance ratio of 7 silicon PV systems over a year and plotted the results against the ambient temperatures over the year. The results showed a clear trend; as ambient temperatures rose above 20 °C a drop in performance ratio was noted. A drop in performance ratio of 9 % over a temperature increase from 20 °C to 35 °C

was noted. This information is important to note for installations of panels in areas where the average temperatures exceeding 20 °C.

A study by the Dhaka University of Science and technology (Adams, 2013) investigated the efficiency of three panel types (monocrystalline, polycrystalline and amorphous) considering environmental factors. The solar cell was modelled by a single diode equivalent circuit and simulated with MATLAB software to investigate the effects of irradiance and temperature on the performance of each material composition panel. Results of the simulations showed that the efficiency of monocrystalline panels was less affected by temperature changes than polycrystalline or amorphous panels.

The study also showed a trend in all three panel types of an increase in efficiency because of increased solar radiation levels which was be expected. The efficiency values plateaued as solar irradiation exposure values reached the panels' maximum capacity. Another study carried out at the King Fahd University, Dharam (Singh & Hankins, 2016) recorded a peak power output difference of 12.5 % between a clean and lightly dusted panel.

Panel tilt can affect the performance of a PV system. In a study by the Masdar Institute of Science and Technology (United Nations, 2013), the effect of tilt angle on annual power yield was investigated. It was found that across two PV systems, the panels that were set at an appropriate tilt angle to maximize irradiance exposure performed better than those set at various angles throughout the year. Although the systems showed different annual yields, they both recorded an increase in annual yield because of tilt angle. It is worth noting that the more efficient system showed a 5 % increase compared to a 2 % in the less efficient system. This points to a snowball effect of system component efficiency producing higher yield values as each component of the system is optimized to improve performance.

3. SUPPORTING HARDWARE AND TECHNOLOGY

PV-system technology such as controllers and regulators can be applied in the PV powered systems to drastically improve the system's performance. A report investigating the implementation of storage sinks and smart control in PV systems (Psimopoulos et al, 2017) concluded that by applying heat sink storage in a solar thermal water heating system, power consumption could be reduced. Coupling this with smart control algorithms that track weather conditions and current system parameters the research group recorded a 26.4% decrease in total energy consumption of the system.

In a similar way to applying heat sink storage that can be drawn upon at a later stage by the system, a PV-powered water processing system can store output water in tanks when the system is performing at levels above that required to satisfy the water needs. On days when the panel is exposed to abundant irradiance and battery cells are fully charged, water can be produced and stored in large tanks on the premises. On days where the solar panels are inadequately supplied with irradiance, the battery cells and the tanks can be relied on for water supply.

4. PRE-TREATMENT FILTRATION

Pre-treatment filtration is the process that involves the use of filters to remove particulate matter which may include (large particles, dirt, sediments and microorganism) prior to further water purification. This is necessary for the production of drinkable water for any water treatment process. Seawater purification comes in many forms. The pre-treatment filtration process is an essential process in RO desalination.

4.1 Present State of Seawater

Seawater contains matter in two forms: physical matter and dissolved particulate. Physical matter includes: algae (especially from brackish water); dissolved ions; colloidal, organic, and biological particulates; and dissolved organic matter (Schneider, 2005).

4.2 Available Pre-Treatment Processes for RO Desalination

4.2.1 Conventional pre-treatment

Conventional pe-treatment refers to removing particulate and colloidal matter through coagulation methods. Coagulation is the process of combining small particles into large aggregates/flocs by neutralizing the charges of these particles (Schneider, 2005). The conventional pre-treatment process has been widely used for seawater reverse osmosis (SWRO). However, the system needs to be carefully designed and diligently operated (Schneider, 2005).

Coagulants can be divided into two categories: those based on aluminium and those based on iron. The iron coagulants include ferric sulphate, ferrous sulphate, ferric chloride, and ferric chloride sulphate (Urrea et al., 2019). Also, there are organic and non-organic (Schneider, 2005). For inorganic coagulants the dose used is 5 mg/L to 30 mg/L and for organic coagulants, 0.2 mg/L to 1 mg/L (Schneider, 2005). Coagulants are not frequently used in this process since they pose a potential risk of damage to the RO membranes (Schneider, 2005).

4.2.2 Beach sand pre-filtration

This is a unique pre-filtration method which uses abstraction of seawater through beach wells along the shore. The capacity of the beach wells depends on the natural hydrogeologic conditions such as coastal aquifer thickness, conductivity etc., and sufficient wave movement to prevent clogging. Flushing supports dissipation of colloids in the ocean (Wilf & Bartels, 2005). There are different configurations for this method, each having its own advantages. Figure 1 demonstrates how this pre-treatment works. The prefiltration method illustrated in Figure 1 requires to be installed near the coastline region.

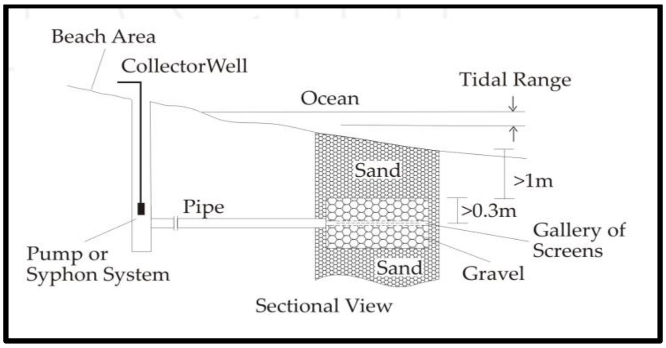


Figure 1: Beach sand pre-filtration (Wilf & Bartels, 2005)

4.2.3 Media pre-filtration

Media filtration is also part of conventional pre-treatment. This type of pre-treatment removes or separates unwanted particles from the substance being filtered. Hence, the material of the membranes is dependent on the substance being filtered (Wilf & Bartels, 2005). Filtration is used to remove levels of suspended solids (turbidity) in the feed. This process can be employed if the Silt Density Index (SDI) is greater than 3 or when the turbidity is greater than 0.2 NTU. Similar guidelines as above are important to follow to avoid fouling in the SWRO membranes (Wilf & Bartels, 2005). This method is commonly regarded as a conventional pre-filtration method depending on the application.

4.2.4 Membrane pre-filtration

This type of pre-treatment involves the use of large ultrafiltration (UF) membranes, microfiltration (MF) membranes and Nanofiltration membranes (NF) to provide a silt index that is below 2. With this method, a plant can operate at its full

potential with reduced downtime (Schneider, 2005). Between NF, UF and MF membranes, UF membrane are the most preferred. This is because MF pore size is big compared to UF pore size [15]. They also have high flux feed then NF. Each of the above membranes can be selected depending on the specific contaminant removal issues, since they have different advantages (Schneider, 2005; Andrews & Laker, 2001).

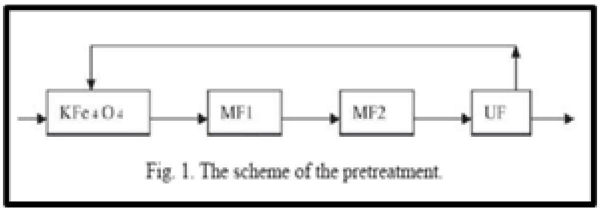


Figure 2: Flow Process of Membrane Filtration (Schneider, 2005)

The aim of filtration is to reduce the feed water pollution with high precision, including iron, silica, algae, and microbial contamination. This controls biofouling and mineralization of the membrane surface. Biomineralization formation is due to adsorption of organisms and absorption of non-organics into the organic matrix (Stover, 2007). Pre-treatment results show that the turbidity of the feed is less than 0.5 NTU while iron concentration does not exceed 0.2 mg/L, silicon concentration does not exceed 0.1 mg/L and removal of microorganism and algae is more than 98 % (Stover, 2007).

4.3 Conventional vs Membrane Pre-Filtration

The conventional pre-treatment processes are cost competitive with MF/UF systems. Capital cost of MF/UF could be (0-25%) higher compered to conventional pre-treatment systems (Schneider, 2005). Energy requirements are significantly smaller for UF/MF therefore they have a lower carbon footprint about 30 % to 50 % (Schneider, 2005). Coagulants increase chemical cost for conventional chemical process optimization. The chemical requirements (therefore costs) for UF/MF are very low, depending on the water quality (Schneider, 2005).

Since SWRO operates at lower flux for conventional pre-treatment, it is expected to cost more to run the plant while UF/MF plants are much cheaper to run, and due to low SDI values for UF/MF, a 20 % higher flux is feasible which reduces total capital costs (Schneider, 2005). The fouling potential of SWRO feed is high for conventional pre-treatment resulting in high operating pressure, requiring frequent cleaning of RO membrane (Schneider, 2005). The net driving pressure is much lower for feed water pre-treated with UF/MF therefore RO membrane cleaning is reduced by 10 % to 100 %. As a result, system downtime is reduced, and the life span of the plant is increased.

Considering the different pre-treatment processes, it is reasonable to rule out the beach sand pre-treatment process because the proposed study is for a portable RO plant that can be used even in rural areas anywhere, not just at the coast.

Cost implications of SWRO are high with conventional methods due to chemical costs and operating costs. If there is high salinity of 3 800 ppm total dissolved solids (TDS) or above, high RO flux and recovery may be limited. However, the operating costs still justify the use of UF/MF pre-treatment (Urrea et al., 2019). Studies show that there needs to be one SWRO clean/year. Further to this, per clean saved per year would lead to a $0.7\ \mathrm{cent/m^3}$ benefit.

UF/MF is consistent in terms of treated water quality from a variety of feed sources. Conventional pre-filtration as defined has more complexities than what can be benefited from it, resulting in many researchers shifting their point of focus to more feasible pre-filtration methods.

5. DESALINATION TECHNOLOGIES

The major desalination technologies can be separated into two categories: thermal desalination and membrane desalination. These categories are further broken down into different processes as shown in Figure 3. Alternative desalination processes are available, but are not traditionally used.

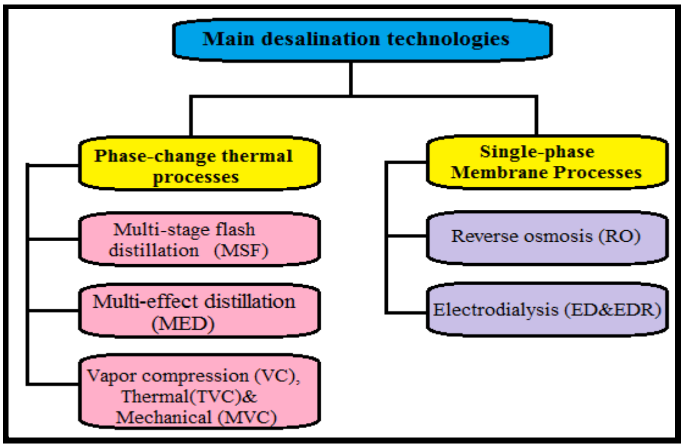


Figure 3: Desalination technologies (Fares, 2019)

5.1. Thermal Desalination Technologies

Thermal desalination is the boiling of saline feed water to produce water vapour which condenses into pure water. Thermal technologies are expensive due to the high energy demand when heating (Thimmaraju, et al., 2018). This technology is commonly found in the Middle East due to the abundance of petroleum which results in low energy cost (Mechell & Lesikar, 2010). Popular large-scale thermal desalination processes include multi-stage flash distillation (MSF), multi-effect distillation (MED) and vapour compression distillation (VCD). Solar distillation (SD) is used for small-scale desalination.

MSF involves multiple chambers (known as stages) through which the saline feed water passes. Each succeeding stage operates at a lower temperature and pressure than the previous stage. In the MSF process, the feed water is heated in a brine heater under extreme pressure. The feed water then flows through different stages where the lower ambient pressures result in feed water vaporization. This is known as “flashing” (Riffat & Shatat, 2014). The vapour is condensed into pure water.

MSF plants are comparatively simple to establish and operate. Additionally, the feed water does not require intensive pre-treatment. On the other hand, MSF is an energy demanding process as it requires 13.5 kWh/m^3 to 25.5 kWh/m^3 (Garg, 2019). The efficiency and water production can be increased by including more stages; however, this also raises capital costs (Zhou et al., 2017). The product water quality is less than 10 ppm total dissolved solids (TDS) (Fritmann, et al., 2008).

The MED process occurs in an array of vessels or evaporators known as effects. The principle of evaporation and condensation is applied by lowering the ambient pressure in successive effects (Riffat & Shatat, 2014). Lower pressures result in a lower boiling point, therefore the water vapour from the previous effect is used as the heating medium for the following effect. The water vapour produced during boiling is condensed and collected as pure water (Thimmaraju, et al., 2018).

The pre-treatment and operational costs of MED are comparatively low. MED is more cost-effective and has a higher performance efficiency than MSF (Thimmaraju, et al., 2018). According to (Antoyan, 2019), MED consumes 6 kWh/m^3 to 22.5 kWh/m^3.

The VCD process is either used independently or in conjunction with another thermal desalination process. In VCD, the heat from the compression of vapour is used to evaporate the feed water (Thimmaraju, et al., 2018). The water vapour is condensed by a mechanical compressor and a steam jet to generate adequate heat to evaporate the saline feed water (Riffat & Shatat, 2014). The VCD process is suitable for small-scale desalination purposes. The process has a low operating temperature and consumes 7.5 kWh/m^3 to kWh/m^3 17.5 (Antoyan, 2019).

SD is commonly used in secluded areas for small-scale desalination purposes. Solar energy is used to separate fresh water from saline water through evaporation. The vapour then condenses on a glass or plastic casing and is stored as freshwater in a condensate trough. The brine solution is left behind for disposal (Thimmaraju, et al., 2018). This process is illustrated in Figure 4. The SD system is cost-efficient as it utilizes solar energy. However, the rate of distillation is slow. SD is not suitable for applications where more than 6 L is required (Garg, 2019).

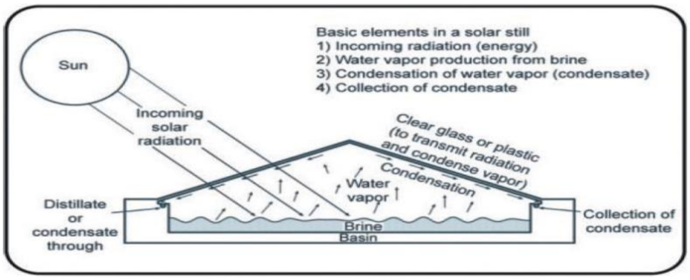


Figure 4: Solar Distillation Process (Zhou et al., 2017)

5.2 Membrane Desalination Technologies

The membrane desalination process uses a semi-permeable membrane to create zones of dissimilar concentration. Additionally, a driving force is required to separate salt from the solution. The most common membrane processes include reverse osmosis (RO) and electrodialysis (ED).

In RO, a pressure is applied to the high-concentration solution. This pressure must be larger than the osmotic pressure to force water through the membrane. The membrane acts as a filter to the dissolved solids (Ansa Aman Ullah, 2015). The basic RO process is depicted in Figure 5. The efficiency of the RO process largely depends on the type of membrane used. Two commonly employed membranes are spiral wound and hollow fine fibre. The spiral wound membrane is preferred due to its high surface area to volume ratio, easily accessible manufacturing materials, and simple replacement (Bodalo-Sontayo, et al., 2004).

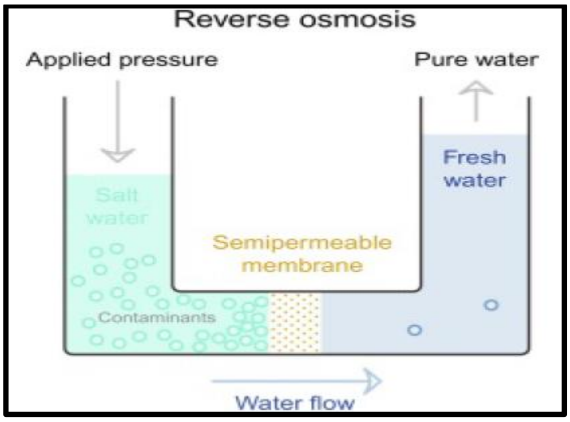
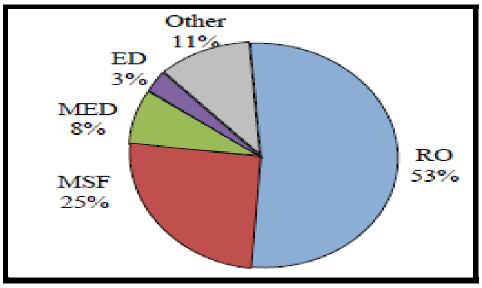


Figure 5: Basic Reverse Osmosis Process (Huang et al., 2020)

After being passed through the membrane in the RO process, the water is almost 99 % pure (Toubi, et al., 2018). The process obtains a recovery rate of 40 % to 60 % (Macmordie Stangton, et al., 2013). The RO system requires less space than other designs and consumes 2 kWh/m^3 to 7.5 kWh/m^3 (Antoyan, 2019). This is around half of the energy consumed by thermal desalination processes. The product water quality is less than 500 ppm TDS (Fritmann, et al., 2008). The RO system experiences less material corrosion compared to MSF and MED systems. The pre-treatment is highly stressed in RO compared to MSF and MED. This is to ensure that the membranes do not get damaged by particles. Experiments conducted in (Mansour, et al., 2020) indicate that energy recovery systems in RO can result in 37 % to 64 % energy savings.

According to a report by the United Nations Economic and Social Commission for West Asia (ESCWA) (ESCWA, 2009), in 1999 MSF produced around 78 % of the world's desalinated water. This declined to 25 % in 2008 due to the rise of RO systems which accounted for 53 % of the world's desalinated water capacity (Figure 6.). This emphasizes the energy savings posed by RO systems.



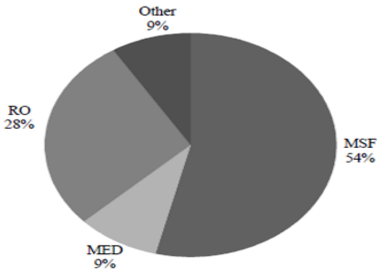


Figure 6: Global Desalination Plant Capacities (ESCWA, 2009) Figure 7: Desalination technology used in the ESCWA region (ESCWA, 2009)

Although RO is energy-efficient, MSF plants are still prevalent in the ESCWA region as shown in Figure 7 (ESCWA, 2009). This is due to the abundance of fossil fuels in those regions.

ED uses electrical potential as a driving force to extract salt from saline water. A selective membrane allows either anions or cations to pass through. The result of this process is pure water with a water quality of less than 500 ppm TDS (Fritmann, et al., 2008). The energy consumption for an ED system is around 0.6 kWh/m^3 to 5.5 kWh/m^3 (Antoyan, 2019). Although the ED process uses less energy than other desalination processes, it is unsuitable for treating seawater. This is because seawater contains 35 000 ppm TDS. ED is conventionally used to desalinate brackish water of around 5 000ppm TDS (R. Singh, 2016).

Emerging technologies include the integration of nanotechnology with membrane desalination technologies. Subramani and Jacangelo (2015) believe that nanocomposite membranes (NM) and closed-circuit desalination (CCD) show extreme potential in the emerging membrane desalination industry. In **NM**, a thin film nanotechnology membrane increases permeability. Although this membrane achieves a recovery rate of 40 % to 50 %, it can obtain a significant energy reduction. **CCD** is implemented in RO systems where the reject brine is recirculated through the process. The recirculation allows for a recovery rate of over 50 % for seawater.

5.3 Alternative Desalination Processes

Alternative desalination processes have been unable to compete with the productive performance of RO, MSF and ED (Riffat & Shatat, 2014). Some alternative processes include freezing and ion-exchange. In the **freezing** process, the formation of ice crystals removes salt ions from feed water. Before the mixture is completely frozen, it is rinsed to remove salt attached to the crystals. Thereafter, the ice is melted, and pure water is produced. The main disadvantage is that the process requires handling mixtures of ice and water which is mechanically difficult (Riffat & Shatat, 2014).

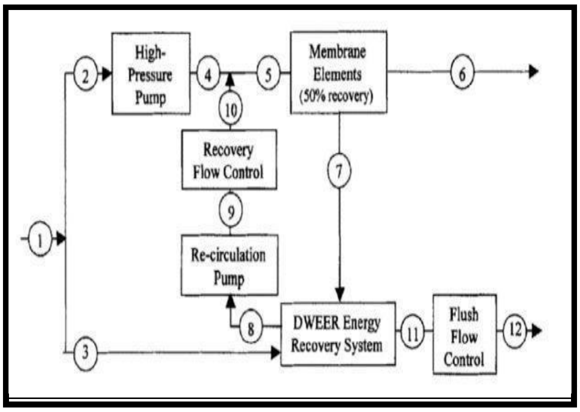
Ion-exchange involves the exchange of ions between chemical resins and the ions from feed water. This exchange allows salt to be extracted from water. Organic or inorganic materials can be used for the resins (Younos & Tulou, 2005). However, it is not feasible to treat seawater using the ion-exchange process (Riffat & Shatat, 2014).

6. ENERGY RECOVERY

6.1 Energy Recovery Devices

The energy recovery system is a crucial part in the desalination of water as it greatly assists in recovery efficiency. Recovery rate and energy consumption are vital factors that influence the energy recovery system design. A high recovery rate under low energy consumption can be achieved by designing and selecting appropriate devices.

Energy recovery devices (ERDs) used in the desalination industry reduce power consumption by obtaining the energy from the concentrate (or brine) waste stream and transmitting it to the feed stream via various methods (Greve et al., 2018). To observe how the ERD works in the desalination plant, Figure 8 displays the recovery system. The RO can produce up to 50 % fresh water, then the other 50 % with brine concentration goes to the ERD as shown in (7) of Figure 8 to be recovered back to the reverse osmosis process. The feed flow at (1) is supplied to (3) as well so that the water supplied mixes with highly concentrated brine so that the water from (3) weakens the brine solution in the ERD and makes the process easier for the reverse osmosis to occur (Infield et al., 2002).



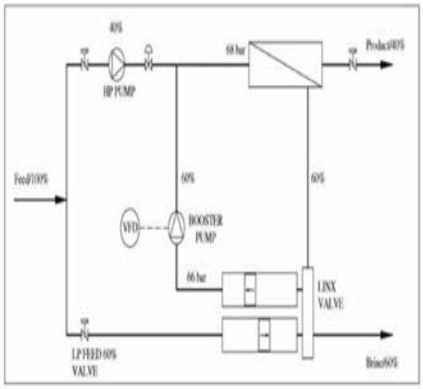


Figure 8: SWRO unit process (Subramani & Jacabgelo, 2015) Figure 9: Work exchanger combined with a RO desalination system (Infield et al., 2002

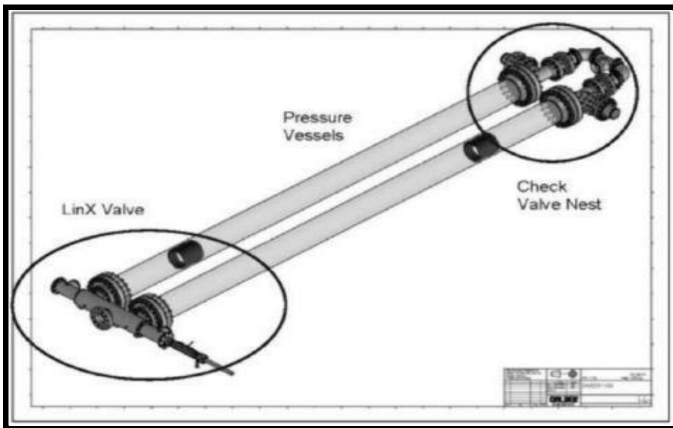
Booster pumps are installed after the ERD to offset the differential pressure on the diaphragm and the pressure loss on the pipeline and the energy recovery system, as shown in the detailed SWRO picture in Figure 9 (Garg, 2019). The main drawback is that this process increases costs.

6.2 Types of ERDs

ERDs can be classified into two types: the positive displacement type and the centrifugal type (Kazmerski et al., 2012).

6.2.1 Positive displacement (piston type)

The piston type of positive displacement works up to a high efficiency of 90 % to 98 %. It can also work at large capacities and has simple processing. The downside for the potable plant is that it is very noisy and is suitable only for large SWRO plants. Figure 10 shows an example of a piston type which consists of two cylinders, a LinX valve, and a check seat.



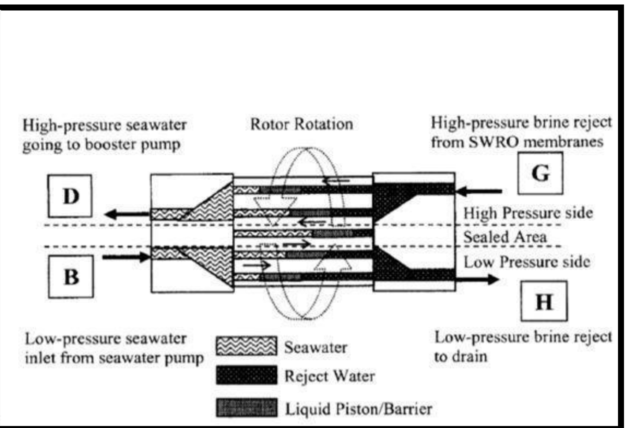


Figure 10: The DWEER work exchange (Garg, 2019) **Figure 11: PX flow schematic (Antoyan, 2019)**

The DWEER is designed to work from 250 000 L/d up to 500 000 L/d, depending on it sizes and specifications (Greve et al., 2018). This is way over designed for a household potable plant which needs 150 L/d to 200 L/d per person.

6.2.2 Ceramic rotary type/pressure exchanger

The ceramic type of positive displacement comprises three essential parts: a rotating rotor for pressure exchange, a sleeve and two end caps (Voutchkov, 2013). A heavy rotor needs electric energy to run and that is a disadvantage in a solar powered desalination plant running on fluctuating solar energy. This ERD has a transfer efficiency of up to 97 %, has a low failure rate, is difficult to corrode and has a low vibration. Also, it does not require regular maintenance (Sani, 2019). The schematic diagram in Figure 11 shows how the PX recovery device works.

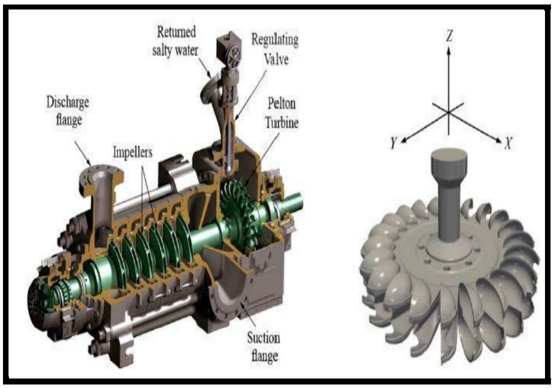
The smallest PX device called PX-15 works with capacity of 48 000 L/d which is not suitable for a small-scale potable SWRO plant (Thimmaraju et al., 2018; Ayang'o et al, 2018).

6.2.3 Centrifugal type

More than 98 % of reverse-osmosis equipment that is used worldwide is of the centrifugal type, which shows how reliable it is (Ayang'o et al., 2018). This type of ERD has two types: the Pelton turbine and the hydraulic turbocharger. All centrifugal types of ERD are powered with hydraulic power from the brine flow (Ullah et al., 2015). This means that the limited solar power energy is then saved for other parts of the plant.

6.2.3.1 Pelton turbine

The high-pressure pump and the turbine part of the ERD are connected coaxially. This means they are driven by the same energy which reduces the costs. This Pelton turbine set-up can produce up to 85 % efficiency (Greve et al., 2018). Figure 12 shows the whole turbine structure and blade structure.



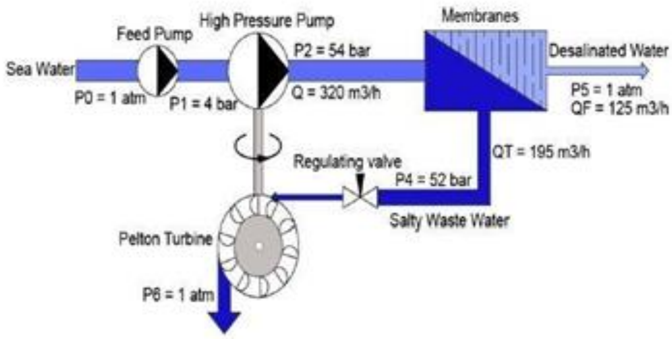


Figure 12: Left: ERD based on high-pressure centrifugal-pump *(Ullah et al., 2015).*

Figure 13: Diagram of the cycle performance package (Ullah et al., 2015

Right: Geometry of the runner (Bartak et al., 2012)

To improve efficiency the geometry of buckets should be looked at, and the speed of water into the ERD adjusted accordingly. Figure 13 shows the schematic of the Pelton turbine in the SWRO plant.

6.2.3.1 Hydraulic turbocharger/ hydraulic pressure booster

The heat transfer coefficients (HTC) components consist of a turbine and pump with blades mounted on the same shaft, like a Pelton turbine. It can produce an overall transfer efficiency of 71 % which is low compared to the other ERDs but for a small-scale plant it can be satisfactory (Shatat & Riffat, 2014). The HTC device can also act as a second pump to boost the water feed into the membranes which improves energy and reduces costs. It runs through hydraulic power from the brine flow. This technology saves a lot of energy. This device can be seen in Figure 14 and Figure 15.

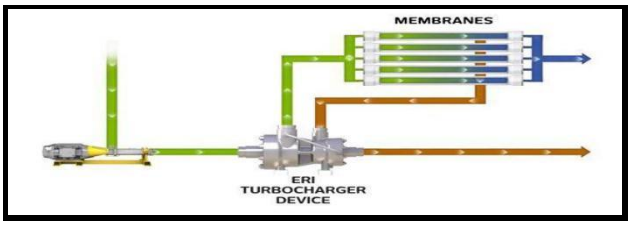


Figure 14: HTC device installation in the plant (Al Toubi et al., 2018)

Figure 15: Hydraulic power operation of HTC (Al Toubi et al., 2018)

To test or calculate the efficiency of and ERD the following general formula can be used:

$$\eta = \frac{Q_{so}.P_{so}+Q_{bo}.P_{bo}}{Q_{si}.P_{si}+Q_{bi}.P_{bi}} \quad (1)$$

Where: Q_{so} – flow rate of the pressurized seawater outlet.

P_{so} – pressure of the pressurized seawater outlet.

Q_{bo}– flow rate of the depressurized brine outlet.

P_{bo} – pressure of the depressurized brine outlet.

Q_{si} – flow rate of the feed seawater inlet.

P_{si} – pressure of the feed seawater inlet.

Q_{bi} – flow rate of high-pressure brine inlet.

P_{bi} – pressure of high-pressure brine inlet [36].

7. POST TREATMENT

7.1 Water Quality

Post treatment commonly includes disinfection and corrosion control (Mansour et al., 2020). Air stripping processes and degasification are also included, provided that hydrogen dioxide and carbon dioxide are present in the permeate water. (Mansour et al., 2020). This process is a standard requirement for most municipalities before any SWRO treated water is delivered as finished water or drinking water, since blending desalinated water with water from other sources can cause significant water quality and infrastructure problems (Younos & Tulou, 2005). Factors that should be considered when treating water from RO include the chemical and biological stability of feed water interacting with the overall distribution system (Younos & Tulou, 2005).

7.2 Dissolved Oxygen, pH and Alkalinity Adjustment

Corrosion rate depends on the amount of dissolved oxygen. The ability of buffering ions is caused by dissolved oxygen (Younos & Tulou, 2005).

7.2.1 pH & Alkalinity Adjustment

pH is correlated with pipe corrosion in most studies (Monika, 1997-2007). pH and alkalinity can be directly related (Ca^{2+} and CCPP) in the system. pH determines the buffer capacity in water sources. Lower pH results in lower buffer capacity which is associated with lower corrosion rates (Younos & Tulou, 2005). pH adjustment can be achieved by adding chemicals such as soda ash lime, sodium hydroxide, carbon dioxide and potassium hydroxide [51]. Adjustment of pH is suitable for water sources with low moderate hardness and alkalinity levels (between 80 and 150 mg/L as CaCO3) (Younos & Tulou, 2005).

The formation of insoluble compounds in pipe walls can be induced by alkalinity adjustment of the distribution system, using similar compounds as listed above. Use of sodium bicarbonate is preferred due to a dramatic increase in pH if sodium hydroxide is used (Younos & Tulou, 2005).

7.2.2 Boron Removal

Removing boron is considered to be expensive and difficult to process especially when dealing with seawater. Second-pass bio-filters and ultraviolet light disinfection are presented as common practice for this process. Research also shows that, to keep bacterial levels low, residual disinfectants must be applied with the aid of free chlorine. Pranav's experiment demonstrates that boron rejection depends on the temperature. The experiment shows an 80 % rejection rate when the system is at room temperature compared to low temperatures (Younos & Tulou, 2005). The pH of boron is about 8.2 in Curacao seawater and contains boric acid. A two stage RO is proposed by studies to lower boron levels. The first stage is to remove salts (RO) and the second stage, using caustic soda, is to transform boric acid to borate which is easier to remove (Younos & Tulou, 2005).

7.2.3 Disinfection

Desalinated water is considered to be an easy challenge when it comes to disinfection due to low TOC (total organic carbon) and particles. The turbidity of desalinated water does not affect the disinfection process (Younos & Tulou, 2005). The target levels to deactivate remaining pathogens in desalinated water is achieved by proper disinfection processes. In the permeate stream, chlorine and the corresponding base can be used for alkalinity recovery.

7.3 Blending Considerations

Blending pre-treated water into permeate product water can stabilize product water reducing some of the above-mentioned issues as well as taste and odour. Blending water can be water from another source. This improves the alkalinity and calcium levels while reducing corrosiveness. Blending does not guarantee water stabilization fully. Permeate needs to be infused with calcium through lime or limestone treatment (Younos & Tulou, 2005).

8. CONCLUSIONS

In this paper, a review of PV stand-alone systems, different desalination technologies available, pre-filtration, post treatment and potential energy recovery has been conducted. The proposed desalination system must be suitable for application in rural communities with access to seawater in South Africa. This requires the system to run off solar-power and be energy-efficient.

The solar capacity evident in South Africa along with the portability of a solar power system when compared with other renewable energy systems, makes solar power a good option for powering desalination plants. The limiting area of the power supply subassembly is battery storage. Building large storage packs is costly and the system cannot afford to be down for a long period of time when it is placed in areas where it is the only source of potable water. All other areas of the plant must be designed to operate at the highest feasible efficiency to reduce power consumption from the system. Supporting hardware like water storage tanks can also be implemented as a feasible means to improved system reliability.

Large MSF plants were previously preferred as the main technology for desalination due to their simple construction and operation. Currently, RO is the leading desalination technology as it consumes less energy and is appropriate for plants of all sizes. SD comes close to competing with RO in terms of energy-efficiency, but is only well-suited for applications with very low water requirements. An RO system's comparatively low energy consumption makes it compatible for use with solar power.

When comparing different types of pre-treatment methods, UF/MF membrane pre-treatment proves to be an effective means to provide the expected water quality. Further studies need to be conducted for more difficult cases to justify any further conclusions about effective processes. Water quality after RO is a concern since studies show that poor pre-

treated sweater may result in RO membrane fouling which decreases the life expectancy of the RO. Experiments and testing will prove useful to accomplish the desired quality of product water.

The most important part is to decrease energy consumption and improve water recovery from brine concentrate. This is possible through the improvement of energy recovery technology devices. Although the positive displacement type mostly operates up to 90 % efficiency, it is suitable only for large-scale SWRO plants, is difficult to maintain, and has significant noise issues. The centrifugal type is suitable for small-scale desalination plants and can be portable. This type is reliable, stable, and easy to adjust. Importantly the centrifugal type works on hydraulic power, saving a lot in energy consumption. The only limiting factor is its lower efficiency. If the efficiency of the centrifugal type of device can be improved through research, then this type of device would be the best for SWRO plants.

REFERENCES

1. *Power Technology, 23 August 2019. Retrieved from http:/www.power-technology.com. (2019).*
2. *Adams, G. Cougulation and Flocculation in Water and Waste Water. pp. 1-4, 2013.*
3. *Alfarisay, S. (Director).. Energy recovery of advanced turbo charge animation. [Film]. Persia.*
4. *Alimirzazadeh, S., Kumashiro, T., Leguizamón, S., Jahanbakhsh, E., Maertens, A., Vessaz, C., Tani K., & Avellan, F. (2000). GPU-Accelerated Numerical Anaylisis of Pump Engineering, Apparatus for Emproving Effeciency of RO System.*
5. *G. Prasanna, G. Manoj Kumar & B. Laxman, "Techno-Economic Feasibility of Solar Powered Drip Irrigation for Tomato (Solanum Lycopersicum)",International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development (IJCSEIERD)Vol. 7, Issue 5,pp, 37-42*
6. *Al Toubi, S., Le, T., Palanca, V., & Nguyen, T. (2018). Seawater reverse osmosis water desalination plant.*
7. *Andrews, W. T., Pergande, W. F., & McTaggart, G. S. (2001). Energy perfomance enhancement of 950 m^3/d seawater reverse osmosis unit in Grand Cayman. Desalination, 135, 195-204.*
8. *Jayanna Kanchikere, A. K. Ghosh & Kalyan Kumar, "Analysis of 80KW Grid Connected Rooftop Solar Power Plant using SISIFO",International Journal of Mechanical and Production Engineering Research and Development (IJMPERD),Vol. 8, Issue 6,pp, 33-46*
9. *Andrews, W. T., & Laker, D. S. (2001). A twelve-year history of large scale application of work-exchanger energy recovery technology. Desalination, 138(1-3), 201-206.*
10. *Antoyan, M. (2019). Energy footprint of water desalination. Master's dissertation, University of Tshwane, Pretoria.*
11. *Ayang'o, S. P., Schirmer, T., Kairies, K-P., & Axelsen, H.,& Sauer, D. U. (2018). Comparison of off-grid power supply systems using the lead-acid and lithium-ion batteries. Solar Energy,162, 140-152.*
12. *E. Shiva Prasad, M. Aravind Goud & R. Ravi Teja, "The Solar Powered Uninterrupted Power Supply System ",International Journal of Electrical and Electronics Engineering (IJEEE),Vol. 8, Issue 5,pp, 1–10*
13. *Ballaji, A., Ananda M. H., Swamy, K. N., & Murthy, V. B. S. (2018). Design analysis and ecomonic investigation of standalone roof top solar PV system for rural India. International Power Journal of Applied Engineering,13(19), 14461-144687.*
14. *Bartak, G., Grischek, T., Ghodeif, K, & Ray, C. (2012). Beach sand filtration as preatreatment for RO desalination. International Journal of Water Sciences,1(2), 1-3.*
15. *Bathia, S. C. (2014). Advanced Renewable Energy Systems. Woodhead Publishing India LTD.*

16. *Raid Al-Khateeb, "Study and Analysis of a Typical Water Distribution Network in Samawa City ",International Journal of General Engineering and Technology (IJGET) ,Vol. 3, Issue 1,pp, 57-66*
17. *United Nations Department of Economic and Social Affairs. (2016). United Nations Sustainable development Goals informations and news page. Retrieved from https://sdgs.un.org/goals/goal6.*
18. *Bódalo-Sontayo, A., Gómez-Carrosco, J. L., Gomez-Gomez, E., Maximo-Martin, M. F. & A. Hidalgo-Montesinos, A. M. (2004). Spiral-wound membrane reverse osmosis and the treatment of industrial effluents. Desalination, 160(2), 151-158.*
19. *Department of Energy, South Africa. Renewable Energy, Retrieved from http:/www.energy.gov.za*
20. *Duranceau, D. S. (2009). Desalination post treatment considerations. Florida Water Resources Journal, November, 1-6..*
21. *Fares, M. N., Al-Mayyahi, M. A., Rida, M. M., & Najim, S. E. (2019). Water desalination using a new humidification-dehumidification (HDH) technology. Journal of Physics: Conference Series, 1279, 012052.*
22. *Fritmann, C., Lowenbrg, J., Wintegens, T., & Melin, T. (2008). State of the art reverse osmosis. Aachen, Institute of Verfahabrenstechnik.*
23. *Garg, M. C. (2019). Renewable energy-powered membrane technology: Cost analysis and energy consumption. In Current Trends and Future Developments on (Bio) Membranes, pp. 85-110.*
24. *Greve, P., Kahil, T., Mochizuki J., Schinko, T., Satoh, Y., Burek, P., G. Fischer, S Tramberend, R Burtscher, S. Langan, & Y. Wada. (2018). Global assesment of water challenges under uncertainty in water scarcity projections. Nature Sustainability, 1(9), 486-494.*
25. *Herzo, A. V. Lipman, T. E., Edwards, J. L. & Kammen, D. M. (2001). Renewable energy: A viable choice. Environment: Science and Policy for Sustainable Development, 43(10), 8-20.*
26. *Huang, B., Pu, K., Wu, P., Wu, D., & Leng, J. (2020). Design, selection and application of energy recovery device in seawater desalination; A review. Energies, 13(16), 4150.*
27. *Infield, M., Maranda, M. S., & Thomson, M. (2002). A small-scale seawater reverse-osmosis system with excellent energy efficiency over a wide operating range. Desalination, 153, 229-236.*
28. *Kazmerski, A. Karagholi, A., & Jones, L. (2012). Economic and technical analysis of a reverse--osmosis water desalination plant using DEEP -3.2 software. Renewable Energy Laboratory, Colorado.*
29. *Khalipour, K. R. (2019). Polygeneration with Polystorage for Chemical and Energy Hubs. Cambridge, Mass.:Academic Press.*
30. *Lenntech. (2016). . Retrieved from http://www.lenntech.com.*
31. *Lopez Gunn, E., & Llamas, M. R. (2008). Re-thinking water scarcity: Can science and technology solve the global water crisis? Natural Resource Forum, 32(3), 228-238, 2008.*
32. *Macmordie Stangton, K. L., Duan X., & Wendel, E. (2013). Reverse osmosis optimization. U.S Department of Energy, Washington DC, USA.*
33. *Mansour, T. M., Ismail, T. M., Ramzy, K. &Salam, M. A. E. (2020). Energy recovery system in small reverse desalination plants: Experimental and theoretical investigations. Alexandria Engineering Journal, 59(5), 3741-3753.*
34. *Manth, T., Gabor, M., & Oklejas, E. (2003). Minimizing RO energy consumption under variable conditions of operation. Desalination, 157(1-3), 9-21.*

35. *Mechell, J. K., & Lesikar, B. (2010). Desalination methods for producing drinking water. A&M Agrilife Extention Service, Texas.*

36. *Nayan F., & Ullah, S. M. S. (2016). Comparative analysis of PV module efficiency for different types of silicon materials considering the effects of environmental parameters. 3rd International Conference on Engineering and Information Communication Technology.*

37. *Psimopoulos, E., Bee, E., Luthander, R. & Bales, C. (2017)Smart control strategy for PV and heat pump system utilizing thermal and electrical storage and forecast services. ISES Solar World Congress 2017.*

38. *Pump Engineering, Inc. (2000). Apparatus for improving efficiency of a reverse osmosis system. U.S. Patent 6139740, 31 October 2000.*

39. *Pyzalska, M. (2007). Literature and study survey: Pretreatment of seawater RO-plants, overview 1997-2007. Linz, Austria: UIHA Wasser Technologie BmbH.*

40. *Sani, A. E. (2019). Design and synchronization of Pelton turbine with centrifugal pump in RO package. Energy, 172(C), 787-793.*

41. *Schneider, B. (2005). Selection, operation and control of a work exchanger energy recovery system based on the Singapore project. Desalination, 184(1-3), 197-210*

42. *Shatat, M., & Riffat, S. B. (2014). Water desalination technologies utilizing conventional and renewable energy sources. International Journal of Low-Carbon Techologies, 9(1), 1-19.*

43. *Singh, R., & Hankins, N. (Eds). (2016). Emerging Membrane Technology For Sustainable Water Treatment. Chapter 6: Desalination and on-site energy for groundwater treatment in developing countries. Philadelphia, PA: Elsevier Science.*

44. *Stover, R. L. (2004). Development of a fourth generation energy recovery device. A 'CTO's notebook'. Desalination, 165, 313-321.*

45. *Stover, R. L. (2007). Seawater reverse osmosis with isobaric energy recovery devices. Desalination, 203(1), 168-175.*

46. *Strohwald, N., Jacobs, E., & Wessels, A. (1992). Development of an ultrafiltration pretreatment system for seawater desalination by reverse osmosis. WRC Report No. 467-1-93. Stellenbosch University, Stellenbosch.*

47. *Subramani, A., & Jacabgelo, J. G. (2015). Emerging desalination technologies for water treatment: A critical review. Water Research, 75(1), 164-187.*

48. *Thimmaraju, M., Sreepada, D., Babu, G. S., Dasari, B. K. Velpula, S. K., & Vallepu, N. (2018). Desalination of water. In M. Eyvaz & E. Yüksel (Eds), Desalination and Water Treatment (pp. 333-345).*

49. *Ullah, A. A., Yasin, S., & Javed, M. U. (2015). Report on reverse osmosis. COMSATS Institute of Technology, Lahore.*

50. *United Nations. (2013). ESCWA Water Developments Report 3: Role of Desalination in Addressing Water Scarcity. New York, United Nations.*

51. *Urrea, S. A., Reyes, F. D., Suárez, B. P., & de la Fuente Bencomo Juan, A. (2019). Technical review, evaluation and effeciency of energy recovery devices installed in the Canary Islands desalination plants. Desalination, 450, 54-63.*

52. *Valavala, R., Sohn, J., Han, J., Her, N., & Yoon, Y. (2011). Pretreatment in reverse osmosis seawater desalination: a short review. Environmental Engineering Research, 16(4), 205-212. https://doi.org/10.4491/eer.2011.16.4.205*

53. *Voutchkov, N. (2013). "Seawater Desalination – Costs and Technology Trends. In Enclopypedia of Membrane Science and Technology. Hoboken, NJ: John Wiley & Sons.*

54. *Wilf, M., & Bartels, C. (2005). Optimization of seawater RO systems design. Desalination, 173(1), 1-12.*

55. *Younos, T. & Tulou, K. E. (2005). Overview of desalination techniques. Journal of Contemporary Water Research & Education,132, 3-10.*

56. *Zhou, J., Wang, Y., Duan, Y. Tian, T, & Xu, S. (2017). Capacity evaluation of a reciprocating-switcher energy recovery device for SWRO desalination system. Desalination, 416, 45-53.*